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Original Article

Planning of alternative countermeasures for a station blackout at a boiling water reactor using multilevel flow modeling

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ABSTRACT

Operators face challenges to plan alternative countermeasures when no procedure exists to address the current plant state. A model-based approach is desired to aid operators in acquiring plant resources and deriving response plans. Multilevel flow modeling (MFM) is a functional modeling methodology that can represent intentional knowledge about systems, which is essential in response planning. This article investigates the capabilities of MFM to plan alternatives. It is concluded that MFM has a knowledge capability to represent alternative means that are designed for given ends and a reasoning capability to identify alternative functions that can causally influence the goal achievement. The second capability can be applied to find originally unassociated means to achieve a goal. This is vital in a situation where all designed means have failed. A technique of procedure synthesis can be used to express identified alternatives as a series of operations. A case of station blackout occurring at the boiling water reactor is described. An MFM model of a boiling water reactor is built according to the analysis of goals and functions. The accident situations are defined by the model, and several alternative countermeasures in terms of operating procedures are generated to achieve the goal of core cooling.

1. Introduction

The Fukushima disaster exposed an inadequate response capability [1]. The control room operators failed to carry out effective countermeasures to terminate core damage and protect barriers due to the loss of monitoring and controlling functions of plants by the serious tsunami. As for complex systems such as nuclear power plants, the cognitive task of planning plays an important role in emergency response. Planning refers to a process of developing an approach for achieving a goal [2]. In most cases, the planned response may include a complicated course of control actions. Generally, there are three potential paths for developing a response plan. The first two paths are based on written procedures or established practices. It is necessary to find the appropriate emergency operating procedures (EOPs), in which rule-based planning is the most straightforward among them. Another path is planning that involves the use of severe accident management guidelines (SAMGs), which is not a pure rule-based approach. Instead, it requires not only specific knowledge to prioritize selected high-level action candidates, but also operation skills when implementing a special high-level action. In the nuclear industry, these written procedures are prepared according to the established defense in depth concept in nuclear safety that can address multiple emergency situations [3,4]. Although the need of generating a real-time plan may be eliminated, appropriate existing procedures must be selected according to the current situations. The selection process can be both event-based and symptom-based. Accordingly, there are several techniques focusing on navigating operators, such as the computer-based procedure [5,6]. However, the Three Mile Island accident coupled with what recently occurred at Fukushima Daiichi nuclear power station (NPS) indicate that unexpected disturbances may extend beyond situations that can be addressed by existing responses such as EOP and SAMG. In other words, personnel, especially the frontline control room operators, may be required to develop alternative countermeasures based on their knowledge of the plant and situation, which is referred to as knowledge-based planning. Since no response plan can be provided, the potential support for activity of planning must be rooted in a model-based approach that can be used to identify a response means. The model should be coherent with human's mental representations of relationships within the major systems in the plant. To support the identification of effective plans, these representations are required to be [7]

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- comprehensive, showing important connections between components and systems;
- flexible so that when standard methods are unavailable, unfamiliar methods can be created; and
- detailed so that sequencing of control actions can be carefully planned.

When operators encounter a planning task, they generally consider the problem within a context of intentions, such as the purpose of a component [8]. Hence, the intentional knowledge of systems is comprehensive to humans and should be reflected in the representation that is used for planning. Functional modeling is able to describe a system's intentions by providing information about goals, functions, components, and their relationships. Multilevel flow modeling (MFM) [9,10], a functional modeling methodology, makes it possible to graphically describe this knowledge in a hierarchical structure. Another characteristic of MFM is that the abstraction level can be chosen to fit the modeling purpose, which means it can be detailed enough to generate information about operable components such as actions. MFM has been used to model action sequences for a normal operation situation [11]. Gofuku [12,13], applied the component information contained in a MFM model to generate one counteraction for an anomaly. In a previous study [14], a system was developed based on MFM to generate procedures that involved more than one operation for accident situations.

This article illustrates how MFM can be used to plan alternative countermeasures for a station blackout occurring at a boiling water reactor (BWR). First, an MFM model of the BWR is built based on analysis of goals and functions. The capabilities of MFM to represent and reason alternatives are explained. The alternatives identified by MFM can be further expressed as a series of operations based on a technique of procedure synthesis. Finally, the situations of station blackout are defined with the MFM model, and several countermeasures are generated to achieve the goal of core cooling. Limitations and future work are also discussed.

2. Modeling theory of MFM

MFM is a graphical modeling methodology that can describe goals and functions of industrial processes. The concepts of means–end and whole–part decomposition and aggregation play a fundamental role in MFM and lead to a modeling in multiple levels of abstraction. As shown in Fig. 1, a system can be described in terms of goals, functions, and physical components along the means–end relation. An end represented by a goal or high-level function can be realized by means of lower level functions or components. In the part–whole dimension, different means–end structures can be aggregated to form a complete model according to the system configurations. The modeling should not be done for each individual component but rather the behavioral interactions between them must be analyzed.

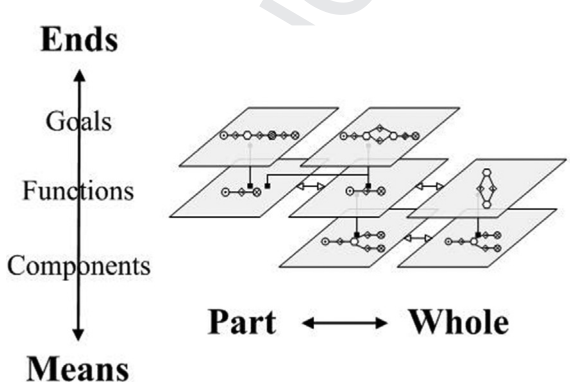

Fig. 1. Means–end and part–whole decomposition in MFM.
MFM, multilevel flow modeling.

Fig. 2 shows the basic symbols of MFM. First, the topmost ends in the model can be represented as objectives and threats, which can respectively be achieved and suppressed by functions. Since industrial processes always involve interactions between different kinds of flows, like material, energy, and information flows, a series of functional primitives are designed to describe these flows in the same abstraction level. The main primitives include source, sink, transport, barrier, storage, and balance. Separation, distribution, and conversion are special derivatives of the balance function to describe in detail different categories of balance in flows. Relations are used to connect between functions and objectives or between each individual function. One kind is influence relations, describing causal dependencies between functions. Another is the kind of means–end relations to describe purpose-related dependencies. MFM can also be used to model control systems, which have both functions and goals as an industrial process [15]. Describing control functions by MFM is based on a separate action theory, which is beyond the scope of the case in this article and will not be further discussed.

To summarize, MFM has features that can satisfy the requirements of representation for planning described in the Introduction: (1) intentional knowledge represented by MFM is coherent with the process of comprehending systems and their relationships, (2) MFM is flexible because it is a common modeling strategy that shows basic knowledge of systems with explicit symbols, which makes it possible to derive various useful information, and (3) the level of abstractions can be selected to fit the modeling purpose. Moreover, MFM also can be used for reasoning about causes and consequence, which will be the foundation of this study that leads to the generation of countermeasures.

3. Functional modeling of BWR

3.1. BWR and its operational objectives

A BWR is a kind of light-water reactor. Fig. 3 shows the system configuration of a GE-type BWR, which is same as Units 2 to 5 of the Fukushima Daiichi NPS [16]. The BWR has only one single power cycle, in which steam is directly produced through the reactor core to drive the turbine generator. There are various auxiliary systems that are designed to maintain normal operation and to ensure the plant's safety during accidents.

The operational objectives of the plant should first be identified in modeling of a system. There are two categories of objectives that need to be achieved in the operation of the BWR. One is for normal operation and the other comprises safety goals for emergency situations. The major objectives that will be shown in the MFM model are summarized in Table 1. Note that objectives in MFM are goals that are directly related to operational parameters of flow functions, such as power corresponding to the flow rate of the heat transfer function. They could be subgoals of goals that are not represented in the model; for example, *obj7* can be treated as a subgoal of the goal of protecting barriers.

3.2. Flow functions of reactor pressure vessel and primary containment vessel

The MFM model of the BWR is shown in Fig. 4. From the objectives, two major flow structures (energy flow structure *efs3* and mass flow structure *mfs1*) are directly identified, and they describe

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